

SYMPOSIUM ON MEAT FLAVOR

CHEMICAL BASIS FOR MEAT FLAVOR: A REVIEW

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ABSTRACT

Considerable research has been done on model systems in which possible meat components have been heated. Many aroma components have been identified including carbonyls, pyrazines, thiols, thiazoles and other nitrogenous and sulfur-containing compounds. Some of these have been identified in the aroma of meat products. Some of the effects of processing on several beef aroma components were assessed. The relationship of concentration of a number of compounds in the aroma and their threshold of detection are discussed, as well as the "GRAS" concentrations permitted. Patents covering the development of meat aroma products are reviewed.

INTRODUCTION

FLAVOR CHEMISTRY has become an important area of specialization in the last 25 years, particularly with the advent of sophisticated instrumentation and separation techniques that permitted identification of trace quantities of materials. Initially, many of the studies dealt with the components of fruit and vegetable flavors, but, beginning in the mid 1960's interesting information on meat flavor began to appear. The chemistry of meat flavor is more like that of coffee or bread than that of fruits or vegetables in that it is temperature dependent. Considerably more is known about the chemical components of other food flavors but this review will be restricted to the components related to meat products, and principally to the red meats.

Current interest in the composition of meat flavor is for the purpose of producing high quality extracts or synthesizing better meat flavors. These will be useful in imparting meat flavor to nonmeat protein analogs, intensifying meat flavor in products made with extenders or in products whose flavor has been attenuated by processing, and in supplying a desirable flavor for use in other than meat products. Detection and recognition of odor compounds are controlled by many factors, most of which are still unknown. Chemical compounds have different threshold concentrations at which they are detected or recognized and these thresholds may depend on solubility in the solvent, specifically fat or water for meat products. Concentration of the compound in the total aroma profile is important; if it exceeds its threshold value the compound may provide an important note, but at levels below the threshold the compound may be ineffective or may react synergistically, antagonistically, or additively with other components to modify the aroma. Unfortunately, very few studies in the chemistry of meat flavor have been quantitative and threshold values are not available for a great many compounds that have been identified in meat aroma. So, the actual role of most meat aroma components in the development of the aroma is unknown. The major compilation for information on threshold values is the ASTM handbook (Stahl, 1973).

Development of meat flavor

Every study on flavor at this time must be considered on its own merits; it is very difficult to extrapolate from one

study to another, and comparisons of results from different studies must be made with caution. There has been no uniformity in the research reported. Different cuts of meat with varying muscle structure have been heated in various ways and with different temperature programs. Collection and preparation procedures have varied, and separation by gas chromatography (GC) has given a variety of results, depending on column packing and sensitivity of instrumentation. As one example of this, Horvat (1976), studying the components in a chicken headspace concentrate, used capillary columns coated with either SF 96 silicone oil or Carbowax 20M. When the former column was used, 28 components were identified, but with the Carbowax column, 36 out of a large number of peaks were identified. Only four compounds were found in common in the two chromatographic separation procedures.

While research with actual meat preparations yield more meaningful data, many studies are carried out with precursor compounds that are, or may be, found in meat and under conditions that presumably occur during cooking. It is, of course, questionable whether all compounds formed in the model systems have meaty odor, or whether they are even found in meat aroma, but much interesting chemistry has developed from model systems and they have provided information about potential reactions that could occur in meat.

The development of meat flavor begins with raw meat which has, essentially, a simple bloody aroma. When heated, however, it develops complex components that evoke a characteristic response. The odor components are formed from compounds present in meat such as proteins, carbohydrates, fats, salts, and minerals. With minor variations, the composition of all meat is similar, but a number of factors may result in modifications discernable in the flavor of the meat. Species differences permit distinguishing among beef, pork, and lamb; nutritional state of the animal (Johnson and Vickerey, 1964) and diet components (Meyer et al., 1960) affect flavor; other factors, such as temperature during growth, may also influence composition of the meat with resultant modification of flavor. More studies are needed in this area of flavor development.

When exposed to heat, components in meat undergo chemical reactions that are governed by temperature and degree of moisture. At 100°C, as in stews for instance, the odor evolved is considerably different from that of a roast at 165°C, even though the interior temperature of the roast may not be greater than 65°C.

What is the chemical basis for meat flavor? At present no single compound with a uniquely meat odor has been identified in meat aroma concentrates or extracts, although some have been reported to be meaty or reminiscent of meat and may be part of the overall flavor complex. Volatile components identified in various meat aroma studies can be classified into a number of classes of compounds. The quantitative relationship of some of these compounds in one study of cooked pig liver volatiles (Mussinan and Walradt, 1974) is shown in Table 1. Furans and pyrazines comprise 70% of the total amount of the compounds identified, and aldehydes another 14%. All of the other components account for the remaining 10% identified. Chang

(1976) suggested that aliphatic and aromatic hydrocarbons, saturated alcohols, carboxylic acids, esters, ethers, aldehydes, and ketones may not be major contributors to flavor. The carbonyl compounds, however, could be important in secondary reactions, as will be shown. Chang indicated that lactones, furanoid compounds, sulfur-containing compounds, and heterocyclic compounds containing S, N, and O may have a large flavor impact.

Dwivedi (1975) listed compounds reported in heated beef, and in heated pork and ham volatiles. The components (Table 2) are grouped in various classes of compounds. Of approximately 200 compounds in each type of meat, beef volatiles contained more alcohols, lactones, and benzene compounds; there were more esters and furans in pork. Approximately equal numbers of acids, aldehydes, hydrocarbons, ketones, and ethers were found in both types of meat preparations. The sulfur components included thiols and sulfides in approximately equal concentrations in beef and pork; however, beef volatiles contained more thiazoles and thiophenes. The nitrogen-containing compounds in both meats included ammonia, pyrazines, quinoxalines, pyrroles, and others.

Carbonyls

Most of the earlier studies on meat flavor resulted in the identification of a number of acids, alcohols, and, particularly, carbonyl compounds. Herz and Chang (1970) reported that the most numerous members of any class of compound identified at that time in meat flavor preparations were carbonyls. These arise principally from lipids and thus are found in the volatiles of fat or fatty meat.

The amount of carbonyls in raw meat changes with age. In one study (Sink, 1973), total carbonyl concentration in *L. dorsi* doubled after 3 days of storage, and monocarbonyl content increased three-fold. Methyl ketones, the major

class of monocarbonyls found, showed a fourfold increase in this period.

A comparison of volatiles from roast beef and from the drippings showed adipose tissue was the prime site of the aldehydes, and fat developed a stronger aroma than the lean (Leibich et al., 1972). Identification of the components separated by GC included 27 alkanals, 12 ketones, 12 alcohols, and 10 aromatic compounds. Of the 9 lactones identified most were present in fat drippings and were absent from the concentrate of lean meat.

Lamb adipose tissue flavor volatiles have been separated into acidic, neutral, and basic fractions (Caporaso, 1976). The majority of the volatiles were in the neutral fraction and consisted of 26 aldehydes, 12 ketones, and 6 lactones among other components. The undesirable flavor of cooked mutton is due to the branched chain and 8–10 carbon unsaturated acids (Wong et al., 1975).

Polyphosphates enhanced the meaty aroma of cooked chicken; all of the carbonyls were significantly lower in the polyphosphate-treated meat but the concentration of sulfur-containing components was increased (Rao, 1976).

Nonenzymic browning, through the Strecker degradation and Amadori transformation reactions, also serves as a source of odorous carbonyls. The condensation of carbohydrates with amino acids during cooking leads to the formation of complex cyclic carbonyls. For example, 4-hydroxy-5-methyl-3(2H)-furanone has been isolated from beef broth and is considered to play a role in beef flavor (Tonsbeek et al., 1968, 1969). This compound has been synthesized by heating amines with xylose, ribose, or ribose-5-phosphate; even glucuronic acid can serve as its precursor during cooking (Hicks et al., 1974). The 5-methyl- and 2,5-dimethyl-4-hydroxy-3-(2H)-furanones can act as intermediates in forming other compounds with roasted meat flavor (van den Ouweland and Peer, 1975). Reaction of these furanones with cysteine, which serves as an H_2S donor, resulted in the formation of four mercapto compounds with a roast meat aroma and six compounds that had meaty aromas when they eluted from the gas chromatograph.

Sulfur

Hydrogen sulfide is the basic sulfur compound that has been identified repeatedly in flavor studies of all species of meat. It can be formed principally from the S-amino acids in meat protein (Hamm, 1966). Among the products of cystine and methionine pyrolysis are mercaptoethylamine and H_2S from the former and methional and methanethiol from the latter. H_2S release increases with time and temperature of cooking, presumably as a result of denaturation of the protein and reduction of -S-S-bonds to -SH. Persson and von Sydow (1973) measured the changes in concentration of H_2S , methanethiol, and ethanethiol in cooked, canned beef. As cooking time was increased from 15 to 75 min, H_2S increased more than threefold. Methanethiol and ethanethiol concentrations increased four-fold and 1.6 times, respectively. In a storage study, however, these authors (Persson and von Sydow, 1974) demonstrated marked losses of H_2S and methanethiol resulting perhaps from interactions with other components in the canned beef, although these were not studied. Increasing temperatures in processing also resulted in less thiol concentration, indicating thermal decomposition of the thiols that formed or the formation of other compounds.

A large number of model system studies have been reported under a variety of conditions too numerous to detail, but a discussion of several such studies will demonstrate the potential for chemical reactions that could occur in meat.

The compounds themselves can, of course, be pyrolyzed

Table 1—Composition of cooked pork liver volatiles

Class	%
Ketones	0.53
Esters	0.56
Hydrocarbons	1.33
Miscellaneous	1.38
Sulfur compounds	2.16
Alcohols	4.21
Aldehydes	14.07
Furans	28.80
Pyrazines	40.96
	94.00

Table 2—Number of volatile compounds in heated beef and pork

	Beef	Pork
Acids	6	5
Alcohols	25	10
Aldehydes	31	39
Benzene Cpd	12	1
Esters	3	10
Ethers	1	2
Furans	8	23
Hydrocarbons	19	13
Ketones	23	23
Lactones	11	2
Pyrazines	32	30
Pyrroles	2	5
Quinoxalines	2	5
Sulfides	8	5
Thiazoles	10	3
Thiols	11	10
Thiophenes	16	10

ductones through the Amadori rearrangement and production of aldehydes and N-containing compounds via the Strecker degradation. A variety of secondary reactions can then occur.

The following reactions were selected as examples from a review of the patent literature on meat aroma. Cysteine was heated with a number of furan compounds substituted in any position but the 5-(May, 1961) or was reacted with 2-8 carbon aldehydes, 2-5 carbon dialdehydes, or 2-8 carbon hydroxyaldehydes (May and Morton, 1961). To obtain a smoked ham or bacon aroma, cysteine was heated with several amino acids, fractionated liquid wood smoke, and protein hydrolysate (May and Ackroyd, 1959). In one patent it was claimed that the addition of methionine gave undesirable odors (Morton et al., 1960); in other patents methionine was added to produce pork flavor (Giacino, 1968a; Bidmead et al., 1968).

Thiamine was reacted with 2-aminoethane (Giacino, 1970) or 1,5-sorbitan fatty acid esters (Hasegawa, 1972) to obtain a meaty flavor. Chicken flavor was produced by heating thiamine with S-containing polypeptides and alkanones or hydroxyalkanones, then adding diacetyl and hexanal (Giacino, 1968b).

In a number of patents, meat flavor is developed in foods by the addition of flavor precursors that require heating during preparation instead of by direct addition of the meat flavor component. It is claimed that the introduction of the 5-methyl-4-hydroxy-2,3-dihydrofuran-3-one or its 2,5-dimethyl homolog results in meat flavor development (Tonsbeek, 1972). A sulfur-containing compound such as thiamine or 3-acetyl-3-mercaptopropanol-1 was heated with an unsubstituted-, hydroxy-, or amino-substituted carboxylic acid and carbohydrate-free protein hydrolysate (Bidmead et al., 1968). A "meat peak" with an empirical formula of $C_{10}H_{14}O_3S$ having an intense pure aroma of freshly roasted meat was isolated but not further identified. A short heat treatment for the formation of the compound was recommended if the material was to be added to a product that was to be heated during preparation to develop full flavor (IFF, 1967).

Finally, a Canadian patent (Hoersch, 1970) claims heating an amino acid mixture with sodium nitrite at pH 5-6 under a layer of oil. No consideration was given to the formation of nitrosamines in this mixture.

More information on the various aspects of the chemical basis for meat flavor, such as isolation and identification of aroma components, model system reactions and kinetics, and the effect of conditions of preparation on the dynamics of component formation, may be found in the references appended to this report which were not used in the discussion.

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Table 6—Pyrazines formed on heating various carbon sources with asparagine

Carbon source	Pyrazine	Methyl pyrazine	Dimethyl pyrazine	Tetramethyl pyrazine
Glyoxal	527 ^a	91	ND ^b	ND
Acetaldehyde	29	51	291	ND
Glycerol	2	7	2	ND
Propionaldehyde	ND	ND	ND	ND
Hydroxyacetone	ND	ND	9725	ND
2,3-Butanedione	ND	ND	ND	2662
Glucosamine	107	252	27	ND

^a Mol.

^b ND = Not detected.

Table 7—Pyrazines on the GRAS list and threshold concentrations

Compound	Threshold (ppm)		"GRAS" level (ppm)
	Water	Oil	
Methylpyrazine	105	27	10
2,5-Dimethylpyrazine	35	17	10
2,6-Dimethylpyrazine	54	8	10
Trimethylpyrazine	9	27	5
Ethylpyrazine	22	17	10
2-Ethyl-5-methylpyrazine	0.1	0.3	2-5

produce pyrazines on heating (Wang and Odell, 1973), casein, heated alone (Kato et al., 1972) or with lactose (Ferretti et al., 1970, 1971) did yield a number of pyrazines.

Shibamoto and associates (1976, 1977) conducted a series of studies on formation of pyrazines and sulfur compounds in systems containing NH_3 and H_2S . With furfural as the carbon source, a number of pyrroles were formed indicating there was an exchange of N for O in the furan ring during the heat treatment inducing the reaction. Furans are products of the caramelization of sugars. Glucose, heated with NH_3 and H_2S , gave rise to 23 compounds that have been identified in cooked meat; ten of these were pyrazines and five were N-containing thiazoles. Increasing the concentration of NH_3 increased total yield of pyrazines and changed the ratio of individual pyrazines formed. This was due in part to the increased concentration of NH_3 available for reaction and in part to the increase in pH which results in greater fragmentation of the sugar, producing more shorter-chain carbon and carbonyl compounds. The normal pH of meat is about 5.5, which would favor the initial steps of the carbonyl-amino acid/amine reactions. As NH_3 is liberated, either from these reactions or from thermal degradation of amino acids, the acidity of the meat may decrease, thus inducing the reactions described by Shibamoto (1977). They also determined effects of temperature on pyrazine formation in this model system. Although some pyrazines were formed at -5°C (after 30 days), significant pyrazine formation began at 70°C and increased to an optimum at 120°C with a 2 hr reaction time. Other investigators found no pyrazines formed at less than 100°C . Thus in roast meat few pyrazines would be expected in the interior which had been exposed to temperatures less than 70°C and most of the pyrazines would occur in the browned surface. It has been reported, however, that at temperatures of roasting meat (165°C) yields of pyrazines are variable. Shibamoto also showed distribution of pyrazines was dependent on several factors including (1) the reactant ratio, i.e., the percentage of unsubstituted pyrazines varied with the concentration of NH_3 ; (2) temperature; and (3) time of heating.

A number of pyrazines are on the GRAS list, approved for food flavorings (Maga and Sizer, 1973). Permitted con-

centrations for several that have been identified in meat flavor are on the order of 1 to 10 ppm (Table 7). The flavor impact of these particular pyrazines has to be due to more than the quantity permitted. Methylpyrazine, for example, has a threshold of 105 ppm in water and 27 ppm in oil; the thresholds for 2,5-dimethylpyrazine are 35 ppm in water and 17 ppm in oil. Trimethylpyrazine, on the other hand, has a threshold of 9 ppm in water and 27 ppm in oil. Although the amount permitted in food flavors may be considerably less than the threshold in many cases, these compounds may interact synergistically with others, also at sub-threshold concentrations, to change or modify the aroma.

Numerous patents have been issued for the use of pyrazines in foods, several of them in meat products. Evers et al. (1972) incorporated 5,7-dihydro-5,7-dimethylfuro (3,4-b)-pyrazine in chicken broth (3 ppm) and beef broth (10 ppm). Pittet et al. (1972) proposed 5-methyl-3,4,6,7-tetrahydro-2(H)-pentapyrazine for a beef soup base and 5,7,7-trimethyl-2,3,4,6,7,8-hexahydroquinoxaline as a bacon flavor, both at 10 ppm, although there was no characteristic meat flavor in either.

Chemical basis of meat flavor patents

Natural meat flavors have been produced as meat extracts or concentrates of meat extracts. However, the present high cost of such products and the desire to control intensity and type of flavor have led to development of meat flavor preparations. Many years ago simulated meat flavor was achieved by blending appropriate spices; then addition of monosodium glutamate or 5-nucleotides added body to these synthetic flavors. Since the advent of new instrumentation and the increase of knowledge of components isolated from meat, both volatiles and non-volatiles, commercial production of meat flavors has been based on conversion of precursors to the desired product. There has been a plethora of patents in recent years, and more products and processes are being patented. Unfortunately, there has been no published critical sensory evaluation of the flavors produced with respect to similarity to meat flavor, flavor intensity, or consumer acceptability.

The basis for formation of preparations with a meat-like flavor is temperature. One type of flavor can be produced by boiling or refluxing, and another type, imparting a roast aroma, is induced at high temperatures with dry heat.

C.G. May and co-workers (1959, 1961), after studying information available in the 1950's, heated cysteine with a monosaccharide, preferably the pentose ribose, in the presence of hydrolyzed vegetable protein to produce a product with a "savory" smell and taste resembling that of cooked meat (Morton et al., 1960). This led to a flood of patents based on these general principles.

Thiamine, which is also present in meat, and particularly in pork, has been included in a number of patents to enhance meaty flavor. Products arising from thermal degradation of thiamine include: S, H_2S , 3-acetyl-3-mercaptopropanol, 3-mercaptopropanol, and 4-methyl-5-vinylthiazole (Dwivedi and Arnold, 1973).

Protein hydrolysates are the base of most meat flavor patents. These are enzyme- or acid-hydrolyzed proteins from yeast, vegetables such as soy, corn or wheat (Giacino, 1968a), and fish after deodorization with charcoal (Morton et al., 1960). Varying conditions of hydrolysis produce protein breakdown products that may yield different flavors. Hydrolysates are mixtures of proteins, peptides, free amino acids, nucleotides, sugars, and other components that, on heating, can produce a meat-like odor which is enhanced or modified by the addition of the precursors claimed in the patents. The principal reaction is undoubtedly the Maillard reaction with the formation of cyclic compounds and re-

directly. If peptides are pyrolyzed, the products formed may depend on the order of the amino acids making up the peptide (Merritt and Robertson, 1967). Sugars have been reacted with S-amino acids and the compounds formed identified. Studies with ribose or glucose and methionine, cystine, or cysteine produced the thiols of methane, ethane, 1-propane, 2-propane and pentane among other components (Arroyo and Lillard, 1970; Mulders, 1973). The aromas reported were not meat-like but included such terms as rotten egg and undescrivable. However, a number of thiols have been reported to possess a variety of meaty notes (Table 3) (Maga, 1976). There does not appear to be a relationship between the meaty note and chemical structure inasmuch as the compounds include mercapto derivatives of furans, thiophenes, and even a pyrazine. Structure, however, may make a difference in the aroma perceived (Table 4). 2-Methyl-3-furanthiol has a sweet, meat, beef broth, or roasted meat aroma, whereas a shift in the substitution to yield 5-methyl-2-furanthiol results in a compound with an undesirable H₂S or burnt, nonmeaty aroma (Evers et al., 1976).

The impact of an odor component on the total aroma depends on a number of factors such as odor threshold, concentration in the material measured, solubility in water or fat (as the major food components acting as solvents), and temperature. The odor thresholds of several simple thiols in water and air are on the order of nanograms to micrograms/L (Table 5). The concentration of H₂S in cooked beef in one study, for instance, was 7000 µg/L. With a threshold of about 1 µg/L the effect of H₂S on the aroma could be expected to be large.

Aroma components in both model systems and meat extracts have been fractionated and the effect of removing classes of compounds on the aroma studied. Barylko-Pikielna et al. (1974) heated methionine and glucose (at pH 6.5–7) at 120°C for 60 min. The aroma was separated into two groups by GC: garlic-onion-sulfide and aldehyde-diacetyl. One peak was "meaty-brothy." Elimination of carbonyls from the trapped volatiles only emphasized sulfury notes, while removal of sulfides eliminated cabbage and onion-type aromas. When mercaptans were removed only breadcrust, brothy, and boiled cabbage odors remained. The brothy peak was removed only after treatment to remove both sulfides and mercaptans. The author suggested that the compound responsible for the brothy aroma was bifunctional, containing both -S- and -SH groups. No identification of the material was reported.

Similar studies with meat preparations have shown that precipitation of sulfur compounds, but not removal of carbonyl compounds, reduced or eliminated meaty notes (Minor et al., 1965).

Although carbonyls do not appear to be directly involved in meat aroma, they are so reactive they could produce aromatic components by interactions with ammonia or H₂S. Thermal degradation of glucose, or other sugars, produces carbonyls such as α-ketoglutaric acid, dehydroascorbic acid, pyruvaldehyde, and diketones which could be available for further reaction. Shibamoto and Russell (1976) heated glucose with NH₃ then bubbled H₂S through the solution. The volatiles' "resemblance to beef odor was unmistakable." Twenty-four of the 39 peaks were identified in the gas chromatogram; 18 of these had been previously reported in extracts from foods. A number of thiophenes found (2- and 3-methyl-, 2,3-dimethyl-, 2,5-dimethyl-, and 2-ethyl-) have also been reported in meat aromas. In this study the authors collected head gas vapors for separation, but in another series of experiments (Shibamoto and Russell, 1977) they extracted the reaction mixture with CH₂Cl₂ and found 68 peaks; of these, 63 were identified and 24 had been reported in beef flavor studies.

Table 3—Thiols with meaty odor characteristics

3-Mercapto-2-methyl-2,3-dihydrothiophene	Sweet, roast meat
4-Mercapto-2-methyl-4,5-dihydrothiophene	Roast meat
3-Mercapto-2-methyl-4,5-dihydrothiophene	Meaty
3-Mercapto-2-methylthiophene	Roast meat
2-Ethylbenzenethiol	Burnt, meat-like
2-Methyl-3-furanthiol	Roasted meat
Pyrazine methanethiol	Roasted meat
4-Mercapto-2-methylfuran	Green, meaty
3-Mercapto-2-methyl-4,5-dihydrofuran	Roasted meat
4-Mercapto-5-methyl-3-oxotetrahydrofuran	Meaty
4-Mercapto-3-oxotetrahydrofuran	Green, meaty
Pyrazinylmethylmercaptan	Roasted meat-like

Table 4—Effect of -S- substitution in furans on favor

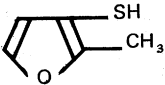
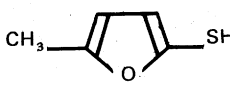
	
2-Methyl-3-furanthiol (Sweet meat, beef broth, roasted meat aroma)	5-Methyl-2-furanthiol (H ₂ S, burnt, sulfury, not meaty)

Table 5—Odor thresholds of some meat sulfur compounds

Compound	Water	Air	Reference ^a
	ppm	ppm	
H ₂ S	—	10 ⁻¹ –10 ⁻⁴	(1,2)
Methanethiol	10 ⁻² –10 ⁻³	10 ⁻² –10 ⁻⁴	(1,3,4,5)
Propanethiol	—	10 ⁻³ –10 ⁻⁵	(1,6)
Butanethiol	10 ⁻³	10 ⁻² –10 ⁻⁵	(1,7,8)

^a 1—Anon. (1930); 2—Dalla Valle and Dudley (1939); 3—Baker (1963); 4—Amerine et al. (1965); 5—Allison and Katz (1919); 6—Wick (1966); 7—Guadagni et al. (1963); 8—Terranishi (1967).

Pyrazines

As mentioned previously, 30–32 pyrazines were identified in cooked beef and pork, and they constituted about 41% of the total aroma components in heated pork liver. Pyrazines would seem to play an important role in flavor perception. For the most part, however, odor descriptions indicate that pyrazines have a nutty or cracker-like note, although a bell pepper odor response is also frequently mentioned. Few, if any, pyrazines have been reported to have a meat-like aroma. Few pyrazines have been reported to occur naturally; they are usually formed through the application of heat.

Studies with model systems involving combination of NH₃ or amino-containing compounds with sugars or other carbonyl compounds, have led to several theories on the mechanism of formation of pyrazines. Newell et al. (1967), with a glucose-amino acid system, and van Praag et al. (1968) using glucose and NH₃, arrived at the conclusion that the reaction required free NH₃ and that the same pyrazines were produced regardless of the amino acid, since it only served as a source of free NH₃. Koehler and his co-workers (1969, 1970), however, demonstrated that amino acid-N will react directly with the sugar system to produce different pyrazines. In addition to the sugars themselves, degradation products of sugars that might occur in meat also react with asparagine to produce a number of pyrazines (Table 6), the type and concentration depending on the carbon source (Koehler and Odell, 1970). Some pyrazines can also be formed by heating such hydroxy-amino compounds as threonine, serine, ethanolamine, and glucosamine (Kato et al., 1970). Although egg and beef albumin did not

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Ms received 3/3/78; revised 6/7/78; accepted 6/10/78.

Presented at the Muscle Foods Division Symposium on Meat Flavor, 37th Annual Meeting of Institute of Food Technologists, Philadelphia, PA. June 5-8, 1977.

Reference to brand or firm name does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.
